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A Method to Forecast Sedimentation Rates Resulting from the Settlement of Suspended Solids Within Semienclosed Harbors

AD A103165

by

Craig H. Everts

COASTAL ENGINEERING TECHNICAL AID NO. 81-6

JUNE 1981

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When a semienclosed harbor is planned for an area where sediments may enter the harbor in suspension, it is desirable to forecast the rate at which those sediments will be deposited. A method to make such a forecast is presented in this report. The harbor shoaling rate (sediment accretion) is the dependent variable. The method is applicable to situations where the harbor is almost totally enclosed; bedload transport is negligible; deposition is nearly uniform throughout the harbor; sediment will not be resuspended (once deposited); and tide or river stage rise causes currents which move water and suspended sediment into the harbor.

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PREFACE

This report presents a method for estimating the sedimentation rate in a semienclosed harbor before construction. Sedimentation is assumed to result when suspended solids carried into the harbor during a rising tide or rising river stage settle out before they can be removed from the harbor as the water level falls. The work was carried out under the coastal engineering research program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Craig H. Everts, Chief, Engineering Geology Branch, under the general supervision of N.E. Parker, Chief, Engineering Development Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

A	plan area of basin
A_b	plan area of basin at sill elevation
a_s	tidal amplitude or maximum river stage variation
c	suspended-sediment concentration
c_i	initial suspended concentration which enters harbor
$\bar{c}$	mean suspended-sediment concentration during the interval $0 \leq t \leq T/2$
d_s	particle size in millimeters
K	sediment-concentration correction coefficient used to calculate M
K_b	sediment-concentration correction coefficient used to calculate P
k_s	correction factor for suspended-sediment concentration which varies linearly with time
M	total mass of sediment which enters a harbor
M_d	total mass deposited in basin
m_v	mass of sediment per unit volume of deposited material
P	part of M deposited in harbor, with $z_s = 0$ and $k_s = 0$
P_s	part of M deposited in harbor when $z_s \neq 0$ and $k_s = 0$
P_{sb}	part of M deposited in harbor when $z_s \neq 0$ and $k_s \neq 0$
S_r	shoaling rate on bottom of harbor basin (not sidewalls)
T	tidal period or duration of a complete rise and fall of a river hydrograph
t	time in hours past previous time of low water
V_{sd}	unit volume of sediment deposited in basin
v_s	particle settling velocity
z_s	sill elevation
α	sidewall slope of harbor basin
η	water surface elevation
ρ_d	bulk density of sediment deposit in basin
ρ_s	density of sediment particles
ρ_w	water density

A METHOD TO FORECAST SEDIMENTATION RATES RESULTING FROM THE SETTLEMENT OF SUSPENDED SOLIDS WITHIN SEMIENCLOSED HARBORS

by
Craig H. Everts

I. INTRODUCTION

Some harbors experience sedimentation largely as a result of the fallout of suspended material. This report presents a method to forecast the sedimentation rate caused when waters laden with suspended solids enter a semienclosed harbor during a rising tide, or rising river stage, and settle out before they can be removed in suspension as the water level subsequently declines. The method can be used in planning harbor maintenance expenses before construction in an area where significant quantities of sediment are transported in suspension. Geometric characteristics of the proposed harbor are considered; consequently, the method may also be used to evaluate design tradeoffs (i.e., sedimentation rate versus harbor size, project depth, and channel characteristics).

II. HARBOR CHARACTERISTICS

The general case of an enclosed harbor basin connected by a channel to navigable waters is considered (Fig. 1). The basin and channel may be of any size and shape as long as the rise and fall of the water surface inside the basin is nearly in phase with and of the same amplitude as that outside the basin. Sidewalls may be sloping or vertical. A sill in the navigation channel may be at any elevation, including the elevation of the channel bottom; i.e., no sill, the most common case for enclosed harbors. A sill is used in high tidal range areas to reduce excavation costs when constructing the basin. It provides flotation for vessels in the basin at low tide stages, but restricts navigation in and out of the basin to times of higher tidal elevations. Harbors in Alaska with such sills are called "half-tide" harbors.

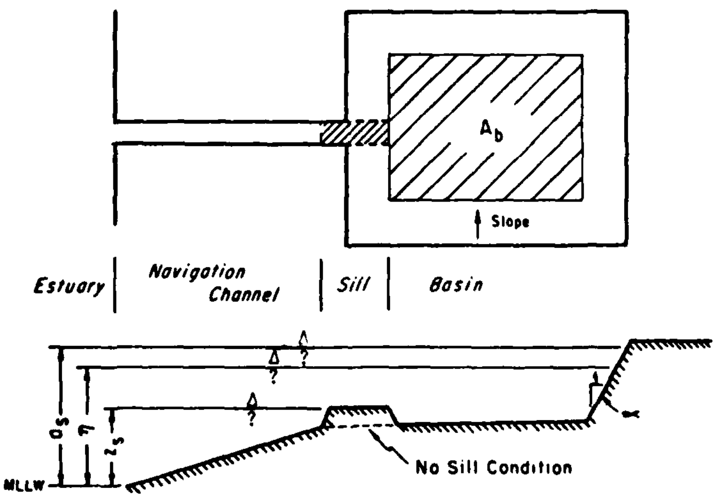

Figure 1. Definition sketch of an enclosed harbor. Three major components of a half-tide harbor are illustrated: basin, sill, and navigation channel. The half-tide harbor is the most general case of an enclosed harbor; in most situations a sill will be absent. When the sill is absent, and where the basin bottom elevation is above MLLW, the basin will be dry at or near the time of low tide. a_s = MHHW tide elevation; A_b = plan area of basin; η = water surface elevation; z_s = sill elevation; α = sidewall slope.

To achieve reasonably accurate results in using the method, engineering judgment is required to assure the following conditions will exist at and near the harbor:

(a) Sediment will enter the basin in suspension; bedload transport will be negligible.

(b) Water will enter or will be discharged from the basin through the channel as the water surface rises or falls in nearby navigable waters.

(c) At any given time the flow in the channel will be unidirectional or nonexistent; i.e., the volume of water that will enter the basin as the water surface rises will be equal to the volume of the basin above the sill. If no sill exists, z_s = basin bottom elevation; if the sill elevation or basin bottom elevation is below MLLW, z_s = MLLW = 0.

(d) Water in the basin will be trapped below sill elevation. When a sediment particle settles below that elevation, even though it has not yet reached bottom, the particle is considered deposited. If no sill exists, bottom scour is assumed to be nonexistent.

(e) Shoaling rates and the sedimentation processes will be uniform throughout the basin; no back eddies or other areas of preferred sedimentation will exist within the basin.

III. PROCEDURE

A mathematical model has been developed in integral form to predict sedimentation rates in enclosed harbors (Everts, 1977b). For many general situations the model has been solved numerically, and the results are presented in this report.

1. Data Requirements.

Information required to use the model includes (a) tidal or river hydrographs at the harbor site, (b) concentration of suspended sediment that will be carried into the harbor, (c) settling characteristics of the suspended sediment, and (d) proposed harbor geometry.

a. Tidal or River Hydrograph. The volume of inflow water to the basin is obtained using the tidal or river hydrograph. In this procedure, a simple cosine function is assumed to approximate the rise and fall of the water surface; i.e.,

$$\eta = \frac{a_s}{2}\left(1 - \cos\frac{2\pi t}{T}\right) \tag{1}$$

where

η = water surface elevation

a_s = tidal amplitude or maximum river stage variation

T = tidal period or duration of a complete rise and fall of a river hydrograph

t = time past low water

b. Concentration of Suspended Sediment. Sediment is assumed to enter the harbor at a uniform concentration, c, through the water column. This vertical uniformity may result from mixing in the channel even where outside waters are stratified. Mixing will usually increase as the ratio of the tidal prism to channel cross section increases.

In many cases the concentration of entering sediment will vary with time in the tidal cycle. Since this variation will affect the time and distance the sediment has to settle to be deposited, time dependence must be considered. When a linear change is assumed, and the concentration at the beginning of the floodtide cycle, c_i, the concentration averaged over the floodtide cycle, $\bar{c}$, and the period T, of the complete tidal cycle are known, a simple relationship is used to account for concentration change with time during a flooding cycle sequence

$$k_s = \frac{4\left(1 - \frac{c_i}{\bar{c}}\right)}{T} \tag{2}$$

where k_s is the correction factor used for suspended-sediment concentration which varies linearly with time. The values of c_i and $\bar{c}$ are obtained from analyses of water samples collected over one or more rising water sequences near the harbor site.

c. Settling Characteristics of Suspended Solids. The rate at which suspended particles settle is a critical factor when determining whether they will be deposited or removed while still in suspension as the outside water surface drops and fluid leaves the harbor. Because a mass of sediment particles in nature displays a wide range of settling velocities, a settling velocity distribution must be considered. For each particle settling velocity, v_s, there is a corresponding particle size, given as sphere diameter, d_s, in millimeters in which the sphere has a density, $\rho_s = 2.7$ grams per cubic centimeter. Caution is recommended when using a grain-size distribution instead of a settling velocity distribution. Grain diameter is often determined in the laboratory as the effective diameter based on Stokes' Law using distilled water. However, particle aggregation in the fluid in which the sediment was collected (often saline) may increase the settling velocity in nature. Therefore, settling velocity distribution should be measured in the ambient fluid at the normal fluid temperature expected in the harbor.

d. Harbor Geometry. The plan area of the basin at sill elevation, A_b, the slope of the basin sidewall, α, and the elevation of the sill, z_s, are required parameters (Fig. 1). These geometric characteristics of the harbor are used to determine the volume of water and the mass of suspended sediment which will enter the harbor during each floodtide cycle. The parameters are also needed to determine the vertical distance through which a suspended-sediment particle must fall to be deposited and the area over which the sediment will be deposited.

2. Solution.

Three steps required to determine the shoaling rate are: (a) predict the total mass of sediment that will enter the harbor; (b) predict the part of that mass which will be deposited; and (c) predict the shoaling rate (increase in bottom elevation) which will result.

a. Step 1--Sediment Mass Entering Harbor. During a rising tide, or rising river stage, the mass of sediment carried into the harbor is dependent upon the concentration of entering suspended sediment, the characteristics of the tidal or river hydrograph, and the geometry of the proposed harbor. For a harbor basin with vertical sidewalls and no sill ($z_s = 0$; Fig. 1), and into which the entering concentration of suspended sediment is constant ($c_i = \bar{c}$) ($k_s = 0$; eq. 2), the total mass of sediment, M, which enters during a floodtide cycle is

$$M = c\ a_s\ A \tag{3}$$

where A is the surface area of the basin. When a sill is considered ($z_s > 0$), but the entering concentration is constant through time ($k_s = 0$) and the sidewalls are vertical, the mass which enters is

$$M = c\ A(a_s - z_s) \tag{4}$$

With a sill and vertical sidewalls, but when the concentration of inflowing sediment varies with time ($k_s \neq 0$), the mass which enters is

$$M = \bar{c}\ a_s\ AK \tag{5}$$

where K is the sediment-concentration correction coefficient. Values of K are given in Figure 2.

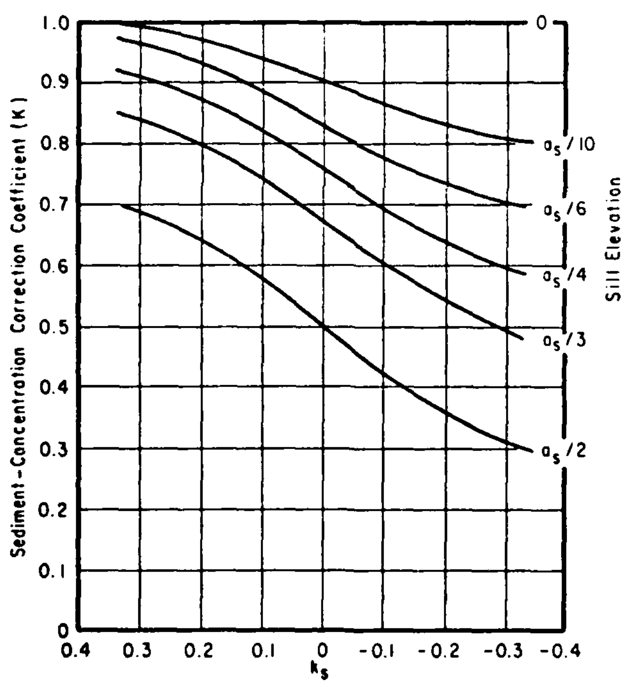

Figure 2. Sediment-concentration correction coefficient, K, as a function of a linear, time-dependent change in suspended-sediment concentration, k_s (see eq. 2) and sill elevation, z_s, where z_s is some part of the maximum water surface elevation, a_s. This figure, used in calculating the sediment mass which will enter a harbor, provides a correction procedure for situations where the entering suspended-sediment concentration varies with time or when the sill elevation is above MLLW.

Equations (3), (4), and (5) are applicable for basins with vertical sidewalls. If the sidewalls are sloping, the average plan area should be calculated for the half-full elevation above the sill. The actual sediment mass input may be slightly larger than that calculated using equation (5) if $k_s > 0$, and slightly smaller if $k_s < 0$ (the difference is small compared to other uncertainties in using this method).

b. Step 2--Sediment Mass Deposited in Harbor. Of the total sediment mass, M, carried into the harbor (eqs. 3, 4, or 5 of step 1), the part deposited is primarily dependent on the settling characteristics of the sediment, the distance the sediment has to settle to be deposited, the time interval during which the suspended material settles, and the elevation of the sill. Figure 3 shows the part of the sediment deposited, P, as a function of tidal range, a_s, and particle size, d_s. For harbors influenced by tide behavior as compared to floods of longer duration, the settling characteristics of disaggregated particle sizes finer than $d_s = 0.001$ millimeter are such that very little material will be deposited in the harbor. For $d_s > 0.03$ millimeter nearly all the sediment which enters the harbor will be deposited. The P values shown in Figure 3 are for $z_s = 0$ and $k_s = 0$ (eq. 2) conditions. Corrections must be made for these parameters when they are not zero.

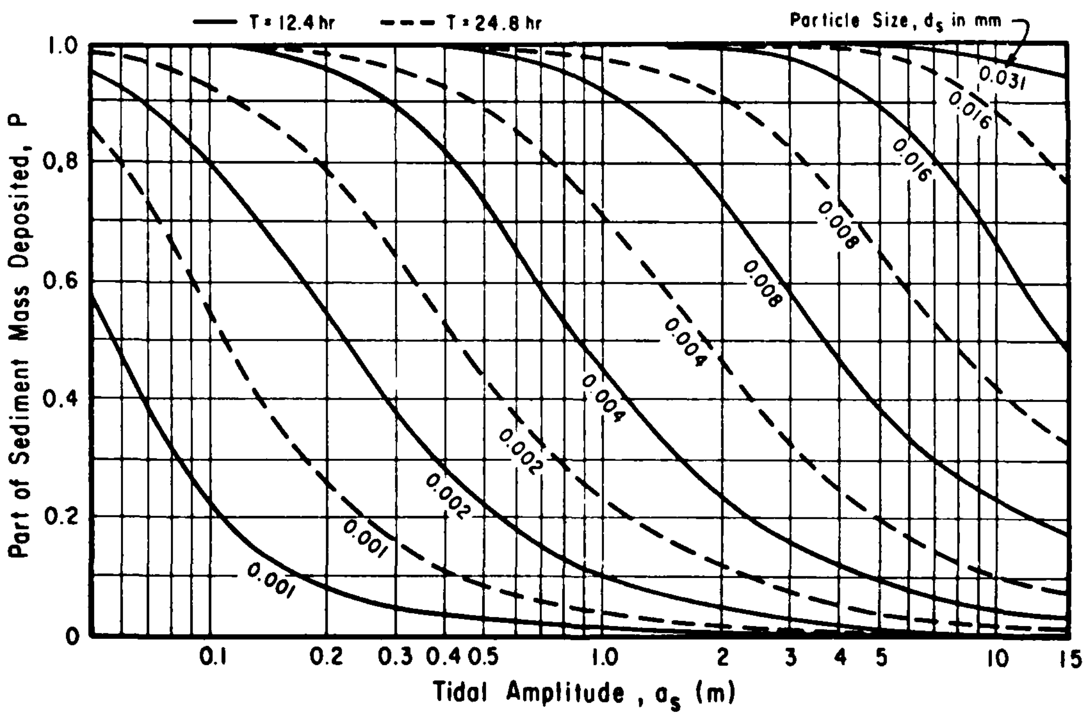

Figure 3. Part of sediment, P, deposited in the harbor basin as a function of tidal range or river rise in the basin, a_s, and particle size. Sill elevation is zero. The sediment concentration entering the harbor is nonvarying with time; i.e., $k_s = 0$ (see eq. 2). Sediment size is related to settling velocity for quartz spheres in freshwater at 20° Celsius.

When the sill elevation, z_s, is not zero, Figure 4 is used to correct the P value.

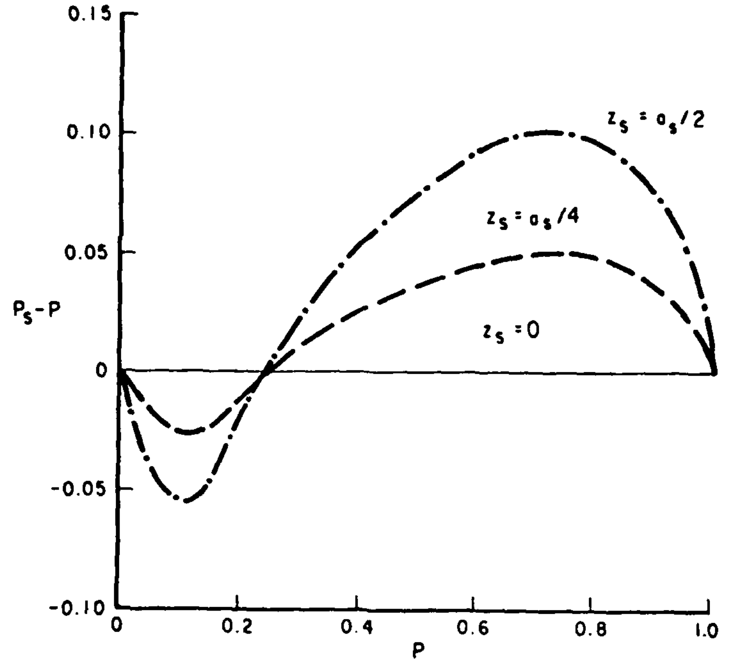

Figure 4. Graph to correct P (see Fig. 3) when sill elevation is not zero. P_s is part of the sediment mass deposited in the basin when sill elevation is included; $k_s = 0$ (see eq. 2).

If the concentration of suspended sediment entering the basin is time-varying (i.e., $k_s \neq 0$), an additional correction, K_b, must be made (Fig. 5) when $0.2 < P_s < 0.8$. The part of the sediment which is deposited in the harbor, P_{sb}, when the sill elevation and time-variable inflowing sediment concentration are considered, is

$$P_{sb} = K_b\left(\frac{c_i}{\bar{c}} - 1\right) + P_s \tag{6}$$

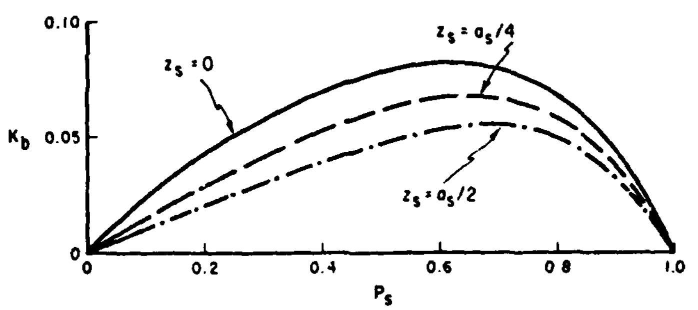

Figure 5. Correction factor, K_b, for time variations in the suspended concentration of sediment entering the basin (used with eq. 6).

The total mass deposited in the basin, M_d, is

$$M_d = M \, P_{sb} \tag{7}$$

c. Step 3--Shoaling Rate in Harbor. It may be desirable to predict the rate of bottom elevation rise caused by sediment deposition. The sediment mass (step 2) must then be converted to sediment volume, and specifically to the volume of the water-sediment mixture which forms the deposit in the harbor. That part of a unit volume of deposited material, V_{sd}, with a density of ρ_d, which is composed of sediment of density ρ_s, is

$$V_{sd} = \frac{\rho_d - \rho_w}{\rho_s - \rho_w} \tag{8}$$

where $0 \leq V_{sd} \leq 1.0$ or ρ_w is the density of water. The mass of sediment per unit volume of deposited material, m_v, is

$$m_v = \rho_s \, V_{sd} \tag{9}$$

and the shoaling rate, S_r, in the basin (not sidewalls) is

$$S_r = \frac{M_d}{A_b \, m_v} \tag{10}$$

The assumption is that sediment which would be deposited on the basin sidewalls moves downslope and is deposited on the basin bottom (A_b = area of basin at sill elevation). Thus, during deposition, the basin sidewall slopes are assumed to remain constant and in their original position.

IV. EXAMPLE PROBLEM

Dillingham Harbor is an enclosed half-tide harbor located off Nushagak Bay, about 550 kilometers southwest of Anchorage, Alaska (Fig. 6). Sedimentation has been a major maintenance problem requiring almost continuous dredging during the summer months. In addition to the high cost, the dredging interferes to some extent with navigation by fishing boats and commercial barges. Flow into and out of the basin is caused by tidal fluctuations in Nushagak Bay. Water entering during floodtide carries large quantities of suspended materials, some of which settle below sill elevation before ebb tidal waters can remove them as the tide lowers.

GIVEN: Data obtained in the vicinity of Dillingham Harbor in 1969, 1973, and 1974 (Everts, 1976b), are:

(a) Tidal Characteristics.

Mean tidal range: a_s = 6 meters

Tidal period: T = 12.4 hours

(b) Suspended-Sediment Characteristics.

Suspended-sediment concentration at t = 0: c_i = 0.8 kilogram per cubic meter (800 milligrams per liter)

Suspended-sediment concentration at t = T/2: c(T/2) = 0.2 kilogram per cubic meter (200 milligrams per liter)

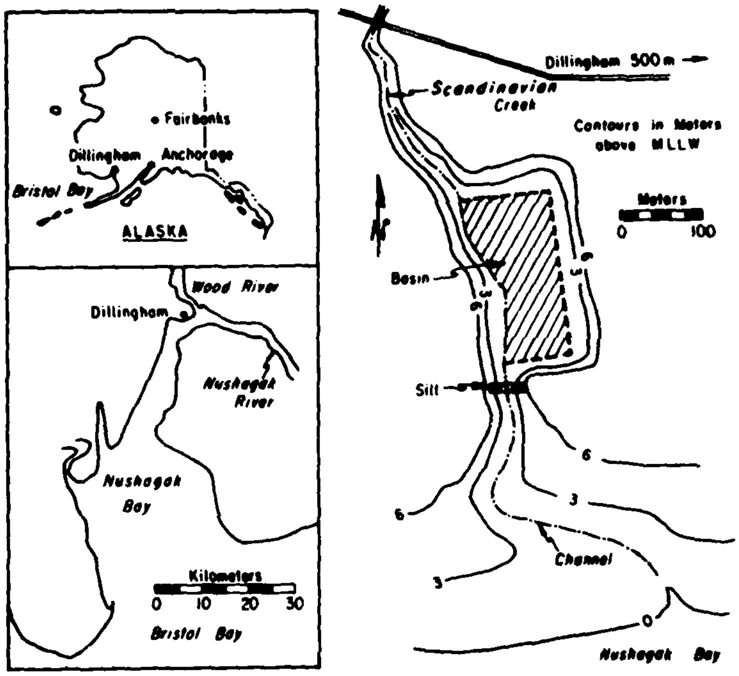

Figure 6. Location map of Dillingham Harbor, Alaska.

Sediment-size distribution (see Fig. 7)

Sediment density: ρ_s = 2.7 grams per cubic centimeter

Water density: ρ_w = 1.0 gram per cubic centimeter

Bulk density of sediment in basin: ρ_d = 1.5 grams per cubic centimeter (estimate from other sources; e.g., see Everts (1976a, 1976b) and Everts and Moore (1976))

(c) Harbor Characteristics.

Sill elevation: z_s = 1.5 meters

Plan area: A = 35,000 square meters (at the half-full basin elevation $a_s + z_s/2$)

Plan area: $A_b(z_s)$ = 21,500 square meters (at the sill elevation of 1.5 meters)

FIND: Estimate the mass of sediment deposited in Dillingham Harbor each tidal cycle; estimate the shoaling rate (bottom elevation increase).

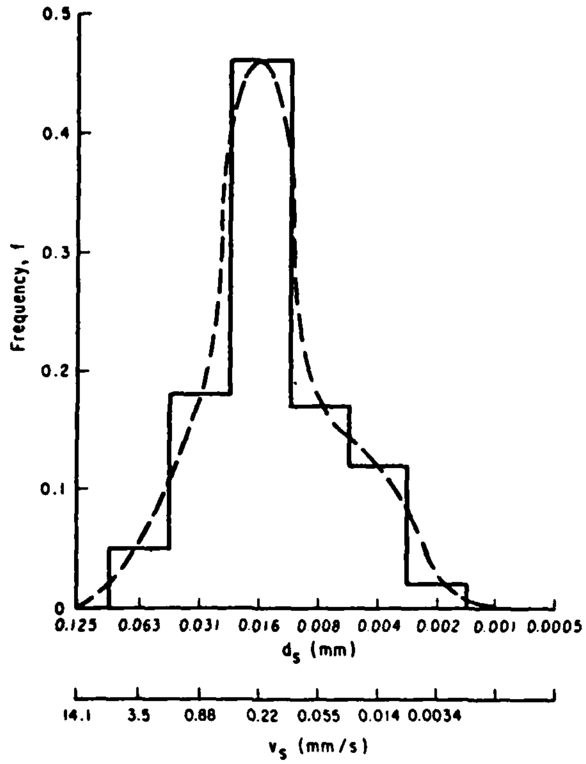

Figure 7. Composite settling velocity and size-frequency histogram of suspended sediment obtained at Dillingham Harbor, Alaska, May to September 1974. Histogram shows mean frequency per v_s or d_s unit shown on the abscissa. v_s = particle settling velocity; d_s = particle diameter in millimeters.

SOLUTION:

(a) Step 1--Determine the Sediment Mass that Enters the Basin Each Tidal Cycle. The mean concentration of suspended sediment, $\bar{c}$, that enters the basin during the floodtide cycle is

$$\bar{c} = \frac{c_i + c\left(\frac{T}{2}\right)}{2} = \frac{0.8 + 0.2}{2} = 0.5 \text{ kilogram per cubic meter} \tag{11}$$

The value of k_s, the correction factor for a time-varying concentration of sediment entering the basin (from eq. 2), is

$$k_s = 4\,\frac{\left(\frac{1 - C(0)}{\bar{c}}\right)}{T} = 4\,\frac{\left(\frac{1 - 0.8}{0.5}\right)}{12.4} = -0.19 \text{ per hour} \tag{12}$$

The sill elevation, z_s, is

$$z_s = 1.5 = \frac{a_s}{4} \text{ meters} \tag{13}$$

where a_s = 6 meters.

The sediment-concentration correction coefficient is $K = 0.65$ when these values are applied to Figure 2. Using equations (5) and (6), the total mass of sediment calculated to be carried into the harbor is

$$M = \bar{c}\left[\frac{A\left(\frac{a_s}{2}\right) + A_b}{2}\right] a_s K = (0.5)(35{,}000)(6)(0.65) = 68{,}250 \text{ kilograms per tidal cycle} \quad (14)$$

(b) Step 2--Find the Sediment Mass Deposited in the Harbor. Since the sill elevation of Dillingham Harbor is not zero, and the concentration of sediment entering the harbor varies through the floodtide (inflow) cycle, corrections must be made for those factors when using Figure 3. However, the settling velocity frequency distribution must first be calculated. This is done for each size-interval shown in Figure 7. The frequency value, f, references that part of the sediment mass with a settling velocity in a single size interval (see Table).

Table. Part of sediment deposited in harbor basin.

$\bar{d}_s$ (mm)	f	P	P_s	P_{sb}	$f \times P_{sb}$
0.125	0	1.0	1.0	1.0	0
0.063	0.05	1.0	1.0	1.0	0.05
0.031	0.18	0.99	0.99	0.995	0.18
0.016	0.46	0.84	0.885	0.92	0.42
0.008	0.17	0.33	0.345	0.375	0.06
0.004	0.12	0.07	0.05	0.06	0.01
0.002	0.02	0.01	0.01	0.01	0
0.001	0	0	0	0	0
Total					0.72

For each sediment-size interval the P value (Fig. 3) is corrected for a sill elevation of $a_s/4$ (Fig. 4), and further corrected for the time-varying concentration of sediment which enters the harbor (Fig. 5; eq. 6). These corrections are shown in the Table. The sum of P_{sb} values shows 72 percent of the sediment that enters the basin will be deposited. The mass of sediment deposited, M_d (using eq. 9), is 49,000 kilograms per tidal cycle.

(c) Step 3--Find the Shoaling Rate in the Harbor. From equation (8) the value of V_{sd} is 0.29, and using equation (9), m_v is 790 kilograms per cubic meter. The summer season shoaling rate, S_r, is 0.0030 meter per tidal cycle (eq. 10).

V. SUMMARY AND CONCLUSIONS

1. Evaluation of Method.

The sediment mass deposited and the shoaling rate (estimated by the method described in this report) resulted in values 12 percent less than those measured in Dillingham Harbor during summer (ice-free) conditions. The method was also tested using shoaling rates and other data collected at and near a large sedimentation tank at Anchorage, Alaska (Everts, 1976a). The predicted shoaling rate at Anchorage was 10 percent less than measured in the tank. In both cases the model predictions were less than that which was actually measured; for a conservative application of the model it is recommended that the M_d value (total mass deposited; eq. 9) be increased by 15 percent.

2. Settling Velocity Distribution.

This crucial factor may vary through time in a rising water cycle, and by time of year. Importantly, it may be highly dependent on aggregation of discrete particles in saline waters. Thus, when compiling the settling velocity distribution diagram, the velocities used should be those which actually may be expected to occur at the harbor site. This means particle settling behavior should be measured in the fluid where it was obtained. Aggregation can occur in glacial-source sediments with low clay percentages such as found in Alaskan estuaries (Everts, 1976c), as well as in sediment suspensions comprised of a high percentage of clay minerals.

3. Sediment Mass Carried Into Harbor.

The part of the sediment which enters the harbor and is subsequently deposited will probably be near constant from one tidal cycle to another, even though the total quantity which enters may vary widely (Everts and Moore, 1976; Everts, 1976a, 1976b). Everts (1976b), for example, reported that the quantity carried into the basin at Dillingham Harbor varied by a factor of three between tidal cycles, but that the part deposited was near constant at 81 percent (range: 76 to 84.2 percent for five tidal cycles). Thus, to accurately predict M_d, a number of tidal cycles or floodflow stages during a river rise must be sampled to obtain representative $\bar{c}$ and c_i values.

4. Effects of Navigation Channel.

Part of the material that enters a harbor may be sediment that was deposited in the navigation channel at a low tide stage and was resuspended during the next rising tide (Everts, 1976b). The amount entering from this source is in addition to that which enters directly from the estuary and which would be obtained from samples collected before the harbor was constructed. The suspended-sediment data presented in the example problem, however, were collected in the channel at the sill at Dillingham Harbor. Compared with other samples collected in the estuary, apparently 60 percent of the sediment carried into the harbor originated in the estuary, and 40 percent came from resuspension within the entrance channel. This channel source should obviously be considered. Cost savings can be achieved when the entrance channel is designed as short as possible (Everts, 1977a).

5. Winter Sedimentation.

Summer sedimentation rates will not prevail during ice-cover conditions. The submerged ice volume reduces the tidal discharge volume of water and suspended sediment to the basin and that reduction can be estimated. Similarly, a reduction in the amount of water and suspended sediment in the channel will reduce the sediment mass inflow from that source.

Because sediment size, water viscosity, and flocculation affect the settling velocity of suspended material in the basin, these factors must be considered on at least a seasonal basis. At Dillingham, median particle size varied from 0.014 millimeter in summer to 0.005 millimeter in winter.

The effect of salt on the settling rate of clay minerals becomes distinguishable at seawater concentrations of about 1 to 2 parts per thousand. Flocculation, and hence the settling rate of the flocs, increase to seawater concentrations of 10 to 15 parts per thousand. Suspended sediment in water samples with a salt content of 0.5 part per thousand at Dillingham during the summer did not appear to flocculate. However, when the winter salinities reached 3 parts per thousand, flocculation might have occurred.

Temperature affects water viscosity and hence the fall velocity of the sediment particles. For example, at 0° Celsius winter water temperature, the fall velocity of an 0.008-millimeter particle is about 70 percent the velocity it would be at 10° Celsius. This must be considered when using Figure 3 (see Fig. 7 of example).

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